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One-dimensional modelling of convective CO_2 exchange in the Tropical Atlantic

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Abstract

Diurnal changes in seawater temperature affect the amount of air–sea gas exchange taking place through changes in solubility and buoyancy-driven nocturnal convection, which enhances the gas transfer velocity. We use a combination of in situ and satellite derived radiometric measurements and a modified version of the General Ocean Turbulence Model (GOTM), which includes the National Oceanic and Atmospheric Administration Coupled-Ocean Atmospheric Response Experiment (NOAA-COARE) air–sea gas transfer parameterization, to investigate heat and carbon dioxide exchange over the diurnal cycle in the Tropical Atlantic. A new term based on a water-side convective velocity scale (w_{*w}) is included, to improve parameterization of convectively driven gas transfer. Meteorological data from the PIRATA mooring located at 10°S10°W in the Tropical Atlantic are used, in conjunction with cloud cover estimates from Meteosat-7, to calculate fluxes of longwave, latent and sensible heat along with a heat budget and temperature profiles during February 2002. Twin model experiments, representing idealistic and realistic conditions, reveal that over daily time scales the additional contribution to gas exchange from convective overturning is important. Increases in transfer velocity of up to 20% are observed during times of strong insolation and low wind speeds ($<6\ \mathrm{m\,s^{-1}}$); the greatest enhancement from w_{*w} to the CO_2 flux occurs when diurnal warming is large. Hence, air–sea fluxes of CO_2 calculated using simple parameterizations underestimate the contribution from convective processes. The results support the need for parameterizations of gas transfer that are based on more than wind speed alone and include information about the heat budget.

Keywords: Gas exchange; Air–water interface; Air–sea interaction; Upper ocean; Convection; Overturn; Buoyancy flux; Diurnal warming; 1-D modelling; Transfer velocity; Carbon dioxide; GOTM

1. Introduction

Accurate estimates of the air–sea exchange of climatically important gases such as CO_2 are vital for addressing the problem of global warming. Understanding the mechanisms controlling exchange allows for

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improved parameterization, and ultimately benefits climate model predictions. A lack of data due to the difficulty of in situ measurement leads to large uncertainties in parameterizing the air–sea flux of gases; modelling studies provide a means of investigating exchange processes, which operate on short ($\leqslant$1 h) timescales, thus improving our understanding.

Approaching the air–sea interface, dominant turbulent processes are suppressed and molecular processes become the dominant control. This leads to strong gradients of properties such as temperature and gas concentrations close to the surface compared with weak gradients away from the interface (Danckwerts, 1951; Deacon, 1977; Jähne and Haußecker, 1998; Donelan and Wanninkhof, 2002; Soloviev and Schlüssel, 2002). Conceptual models of the air–sea interface divide the boundary layers either side into turbulent outer layers and diffusive inner sublayers. Since the diffusivity of CO_2 in the atmosphere is much greater than that in the water, the flow across the interface is limited by the resistance in the diffusive aqueous boundary layer. In addition solubility, which is a function of temperature and salinity, plays an important role (Weiss, 1974). CO_2 is poorly soluble in water resulting in the liquid phase controlling the exchange of mass.

The flux of a gas across the air–sea interface is determined by the product of the gas transfer velocity, which characterizes the resistance to gas exchange across the boundary layers, and the air–sea concentration difference, which is the driving potential. Conventional estimates of air–sea exchange rely on simple, empirical, wind-speed dependent parameterizations of the gas transfer velocity (Wanninkhof, 1992; Liss and Merlivat, 1986; Wanninkhof and McGillis, 1999). However, a number of physical processes contribute to gas transfer across the interface. These include penetrative convection due to heat loss (Jähne and Haußecker, 1998; Csanady, 1997), shear due to wind forcing, microwave breaking at moderate wind speeds (Zappa et al., 2001) and bubbles at high wind speeds (Woolf, 1993; Woolf, 1997).

In regions with low or intermediate winds and strong insolation, changes in the heat budget and ocean circulation may have significant feedbacks on air–sea gas exchange and conventional estimates are likely to underestimate the amount of exchange taking place (McGillis et al., 2004). Questions arise such as: Is the net effect of underestimated convective gas exchange important when integrated over longer timescales e.g. monthly averages?

Diurnal warming can occur in the upper ocean wherever solar heating at midday is greater than the heat lost from the ocean surface, but is more significant where winds are fairly light. Large regions of the world ocean are susceptible and temperature differences can exceed 6 °C in extreme cases (Stuart-Menteth et al., 2003). The resultant nighttime cooling may drive enhanced gas transfer (McGillis et al., 2004).

Fluxes of CO_2 will be appreciably higher when the surface is cooling, as heat loss will contribute to the turbulent mixing via buoyancy forcing within the aqueous boundary layer. Gas transfer will also be modified where the mixed layer deepens, entraining dissolved gases from below (MacIntyre et al., 2002). Thus the daily cycle in oceanic surface mixed layers becomes important. Lombardo and Gregg (1989) and Brainerd and Gregg (1993a,b) investigated cycles of nocturnal convection and diurnal re-stratification in the Pacific Ocean during PATCHEX; daily observations showed that the ocean lost heat and buoyancy starting several hours before sunset and continuing a few hours after sunrise. Anis and Moun (1992) and Anis and Moun (1994)

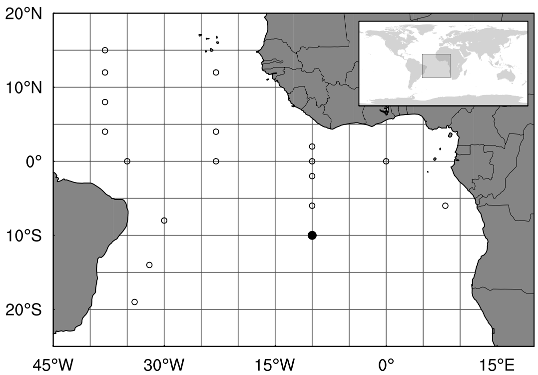

Fig. 1. Study area and location of the PIRATA array of ATLAS moorings in the Tropical Atlantic. The filled black circle represents the PIRATA mooring located at 10°S10°W. *Source*: TAO Project website.